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MORPHOLOGICAL STUDIES OF NOCTILUCENT CLOUDS

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ABSTRACT. Morphological investigation constitute an important part of the problem of noctilucent clouds. Geometrical conditions of noctilucent cloud observations from the surface of the earth and from different levels of the atmosphere are shown. The photos of the crape, bands, waves and whirls of noctilucent clouds are seen as well as an example of perspective distortion and mutual screening of wave formations when observed at a small angle (15°). Further morphological investigations should be developed to determine the true physical nature of each type of structural formation and the thermodynamical conditions of their origin.

Morphological structure is a characteristic feature of noctilucent clouds. /92* The literature includes many fine examples of the detailed study of the external picture of the highest clouds over our planet. Accurate expressions and descriptive comparisons have frequently been used to describe their complex morphological structure as fully and intelligibly as possible. Some have been retained to this day. A special morphological classification has proven itself to be more useful in systematic observations over a large network of stations. It is based on the principle of the genetic community of the countless various shapes of cloud forms according to the character of their motion and the probable physical conditions of their formation. On this basis has begun a systematic study of the morphology of noctilucent clouds. Especially great observation material was obtained during the periods of the International Geophysical Year and the International Year of the Quiet Sun. According to special instructions, all observed structural formations were recorded in individual special notebooks at 15-minute intervals for each appearance of noctilucent clouds. Slow-motion films and multiple photographing yielded documentary material which was then subjected to morphological processing. The first tests at laboratory simulation of various structural forms of noctilucent clouds were taken [1]. (The first results of laboratory experiments and natural observations permit us to express some opinions on the morphological nature of noctilucent clouds.

Observations

The basic factor determining the visual visibility of noctilucent clouds is the amount of contrast between these clouds and the surrounding background of the twilight sky, depending on the brightnesses of both the clouds and the sky. Both values underwent continuous change for various reasons. V. V. Sharonov examined this question in detail in [2].

* Numbers in the margin indicate pagination in the foreign text.

The position of the observer relative to the field of noctilucent clouds under study is also of great importance. Figure 1 shows schematically three of the more general variations of this positioning. Let the noctilucent cloud actually exist in the zone VDMKS. For simplicity in the diagram, the plane of the sketch corresponds with the north-south directions. The solar rays emanate from left to right and are also found in the plane of the sketch. The tangential ray TS indicates the geometrical boundary of the earth's umbra and the illumination of the noctilucent clouds. Although clouds also exist to the right of point S, they are not visible because they are not illuminated by

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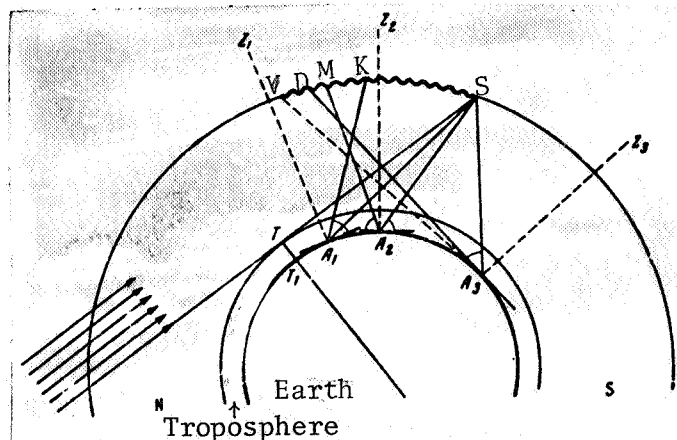


Figure 1. Diagram for the Positioning on the Earth's Surface for the Observers of Noctilucent Clouds.

solar rays. The least distance from the tangential ray TS to the earth's surface will be in the terminator region TT_1 .

According to data by V. G. Fesenkov [3], this distance equals the thickness of the troposphere, i.e. approximately 10 km (for the middle latitudes). The observers are at points A_1 , A_2 and A_3 . The planes of the horizon for these points are indicated by the heavy segments -- the tangents to the earth's surface. The directions to the zenith from each point are indicated by the letters z_1 , z_2 and z_3 respectively.

For the observer located at point A_1 , the sun has dipped slightly below the horizon, i.e. the negative angular altitude of the sun will be $-h_{\odot} \approx 2-3^\circ$. The twilight sky on the northern side and in the region near the zenith is so bright that it dims the light of the noctilucent clouds in the zone VDMK. Only on the southern side, low over the horizon, does the twilight sky fall somewhat behind the noctilucent clouds in brightness, so that they are visible in the region KS.

Observer A_2 sees the noctilucent clouds in the circumzenithal region MKS. In the region VDM, the clouds are dimmed by the bright background of the twilight sky and cannot be observed visually. Such a position corresponds to conditions when $-h_{\odot} \approx 3-5^\circ$. From the morphological viewpoint, this position is advantageous in that observation is performed at a right angle to the cloud cover and consequently the affect of perspective distortion is least felt. However, the contrast of the noctilucent clouds against the background of the twilight sky at the zenith is nevertheless low, because the overall illumination of the lower atmosphere in the region of the observer is too great and creates diffusion of the light from the bright twilight section of the sky on the horizon.

Observer A_3 sees the noctilucent clouds in the northern half of the sky

close to the horizon. Portion VD cannot be seen from point A_3 because it is below the horizon. Clouds in the region of point D are found on the level of the horizon, i.e., approximately 1000 kilometers from the observer. The angle DM for observer A_3 equals approximately 9.5° . Consequently, the surface of the noctilucent clouds located behind the horizon ($h = 0 - 5^\circ$) is observed at a very small angle ($h = 9 - 12^\circ$), i.e. almost edgewise. Perspective distortion of the relief and structural details is so great that most of them merge into a continuous illuminous field. Therefore, for morphological study, only those portions of noctilucent clouds are suitable which are no greater than 500 to 550 km from the observer, i.e. which are located no less than 5 to 6° over the true horizon.

The structure of the clouds is recorded and deciphered more easily the closer the observation point is, but at the same time the cloud area accessible to observation decreases. This results in the fact that at an angular altitude greater than $30 - 40^\circ$, large-scale structural formations lose their overall shape and cannot be identified by the observer. Thus, for large-scale morphological studies, the best observation conditions are within the range of angles from 5 to 6° to $30 - 35^\circ$. To study "small" details, observations should be carried out at a shorter distance, i.e. when the cloud is at the circumzenithal region.

If the observation point (position) is on board an aircraft capable of flying at 30 to 50 kilometers altitude, this permits overcoming the screening effect of the lower cloud cover and the bright background of the blue daytime sky; observation duration is increased many times because the noctilucent clouds can be observed not only at twilight but during the day as well. From point N_1 (Figure 2) the entire illuminated cloud field VS is accessible to

observation. The moving observer can operationally select the most suitable position, from which either the structural formations under study are best visible or a previously unstudied portion of the indicatrices of the cloud distribution is accessible to observation, etc. It is also easier to determine the true limits of the spread of noctilucent clouds and their macrostructure.

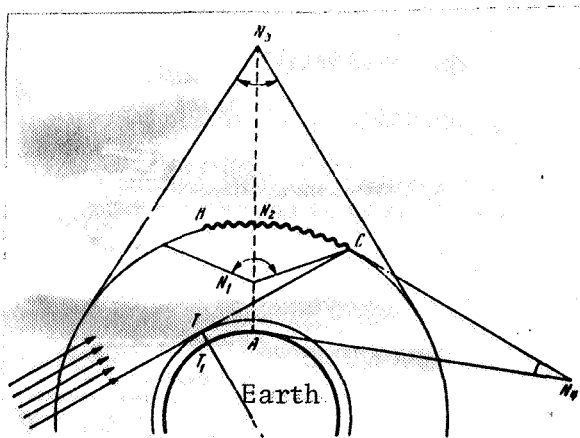


Figure 2. Diagram of Possible Locations for Observation of Noctilucent Clouds on the Upper Atmosphere.

If the observation point is at the level of the noctilucent clouds (N_2), morphological studies will be limited by the unfavorable position of the observer. Nevertheless, the position N_2 has several substantial advantages in observing the aerosol stratification of the mesopause and various types of measurement of

the optical properties of clouds.

Morphological and other studies of a layer of noctilucent clouds from artificial earth satellites also is of great interest. The observation of a disturbed layer of the mesopause from overhead (position N_3) have decided advantages. From an altitude of 200 to 300 km and above, noctilucent clouds may be easily distinguished in the region of the twilight illumination of the atmosphere, i.e. close to the earth's terminator. Against the background of the darkened earth's surface these clouds can easily be observed as a glowing, semi-transparent undulatus layer. The elongation of the scattering diagram [2, 4] will determine the great specular brightness of the cloud field at the solar azimuth. Studies of the macrostructure of noctilucent clouds and the limits of their planetary distribution are more advantageous.

From position N_1 , the studies of the aerosol stratification and optical properties of the earth's atmosphere are of interest. These questions have been examined in detail in the works by V. G. Fesenkov and G. V. Rozenberg (this collection).

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Morphological Structure.

The crape of noctilucent clouds is a fog-like shapeless mass which is almost always present in noctilucent clouds and frequently fills the space between other morphological formations [5]. Figure 3 shows an example of a bright crape during the appearance of very bright noctilucent clouds on 10/11 July in 1951. Here part of the crape is located below the other shapes and shields them from the observer. Note also its nebulous, flocculent and extended fibrous structure. The external evolution of the crape is quite complex and almost completely unstudied.

Experimental observations have at times noted the appearance of the layer separately, without other shapes. In such cases, other structural formations also usually appear 20 to 30 minutes. Then the crape is a sort of precursor of the appearance of the characteristic shapes. Sometimes the crape remains the only shape of noctilucent clouds, usually those of little brightness. Such observations always arouse great doubts as to their reliability. Tests in photographically recording the crape individually from other shapes have as yet yielded no reliable results. To do so we need specific methodological approaches which would permit us to separate the crape-covered area with sufficient contrast and study its structure. This task is not hopeless with the present state-of-the-art in photographic technology. Using the newest information on polarization and the spectral characteristics of light in noctilucent clouds, we may select the corresponding photographic conditions which will yield the optimum results.

With high-transmission binoculars with a wide field of vision, the crape is more visible and its patchiness and the light, flickering glow are more reliably observed. When observing only the crape, the observer usually

incorrectly logs the existence of noctilucent clouds having shape "1" and without leaving his post he watches the sky continuously, awaiting the appearance of more complex shapes. Several nights can be spent in such waiting. The twilight sky, filled with weak crape in some areas, has a unique bluish-white shade. The experienced observer carefully and almost ceaselessly tracks the twilight sky. Also, the longer the delay in the appearance of the clearly outlined shapes of noctilucent clouds, the brighter they appear. After this, there occurs a sort of discharging of the atmosphere and the twilight sky on the following dates, under the same geometrical illumination conditions, has decreased brightness and a dark blue-violet color without any indications of a crape.

Bands. In conformity with the classification of the morphological structure of noctilucent clouds, bands and streams are genetically associated with the evolution of the crape. We should keep in mind the drag caused to the shape of the flare by air current and the formation of broad nebulous bands out of it. At a distance of 600 to 700 kilometers, these bands appear to be rather clearly outlined. From a closer distance (approximately 100 km), however, they are similar to the blurred, nebulous bands which are quite visible in the upper section of the photograph shown in Figure 3 and differ little from crape. It is assumed that when there are local air currents in the mesosphere the crape is stretched out into more clearly shaped bands which are designated "streams" in the classification. Figure 4 shows an example of photographing such shapes in noctilucent clouds.

Unfortunately, observers pay little attention to these formations. Frequently the crest of sky waves are taken as belts and streams. There is little documentary material in slow-motion photography. The speed of motion for these structural formations has not yet been determined. On the basis of existing motion picture material and general considerations, it is proposed that the motion occurs along the band and stream. However, this is so far insufficient for more definite conclusions. In general, O. B. Vasil'yev doubts the possible existence of these structural formations [6]. According to data from photographic photometry, he finds a great similarity between the photometric sections of the bands and wave formations. A miniature "Zorkiy" with a 24×36 mm opening and an $f = 50$ mm objective and using 35-mm roll film was used. It is impossible to dispute the results because careful observations were taken. Another picture evolves with the identification of the types of structural formations. Visually it is quite difficult and sometimes completely impossible to distinguish the belts and streams from the sky waves, whose crests are often many hundreds of kilometers long. They are quite similar externally. In miniature photographs, the crests are also very similar to the bands and streams. Only the use of large-scale photographing and slow-motion film permit distinguishing the wave formations according to their characteristic relief and phase motion. Real bands and streams have no wave-like nature, at least not with the large-scale photography methods which have been used up to now. During the IGY and later, morphological studies were taken from photographs of noctilucent clouds which had been taken with aerial photography equipment which had been reequipped for ground photography. The cameras had fast lenses with a main focal length of 25 and 50 cm; the film was roll film 19 cm wide and with an image area of 18×24 cm. The quality of a photographic image is known to be a function of the resolving power of the lens.

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Morphological analysis demands large cameras with a long focal range and a high resolving power.

It should once more be noted that the bands and streams of the noctilucent clouds are almost completely unstudied, and therefore information on the morphological and dynamic nature is unreliable. Future investigations may introduce corrections into present-day concepts concerning their nature.

Waves. Photographs of noctilucent clouds often show wave-like formations. A 1-km thick cloud layer is spread along the wave surface of the mesopause, reproducing the wave oscillations of the colder boundary layer of the atmosphere (Figures 3 to 6). Encountering such a temperature minimum, cloud particles and sublimation centers increase as a result of the additional sublimation of water vapors. Emerging from the cold layer, the ice particles evaporate. As a result, the sharp outlines of the dynamically active wave layer in the atmosphere are maintained. Similar phenomena occur during the formation of wave forms in high-altitude cirrus clouds in the troposphere.

In studying the wave forms of noctilucent clouds, "upside-down" photography is recommended. Then the wave surface of the noctilucent clouds is observed in the same way that man looks at the wavy surface of water. Everything that has a wave nature is easily observed in the inverted photographs. Figures 5 and 6 show two photographs of small sections of the cloud field in an inverted position.

Measurement results for several geometrical parameters of the wave formations are of interest. Type III combines the wave shapes with a wave length from 10 : 20 km to 50 - 100 km. Such waves are easy to find in slow-motion films and large-scale photographs.

Two large waves are readily visible in the lower section of the photograph in Figure 5. The front of these waves almost exactly corresponds with the observer's line of sight. Knowing the distance to the wave formation (650 km) and allowing for perspective distortion, we may determine the angle for the steepest portion of the wave surface. This angle at times reaches 30° , while the height of the wave is around 8 km.

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Figure 6 a and b shows part of the wave surface in noctilucent clouds photographed twice at 10-minute intervals. The vertical section of the wave surface makes the relief of the cloud field all the more clear. The rear surface of the closer large wave cannot be seen because it is screened by the crest and forward inclined surface. The maximum steepness for this wave is 40° .

During a short time period, the wave reached a height of 10 km. The velocity of the phase motion was slow -- 24 m/sec. The waves began to arise at 00 hours 25 min on 7 July 1951 on a relatively quiet wave surface (type IIIa). Their maximum development was reached at 00 hours 50 min, and at 01 hours 30 min there was no trace left of them.

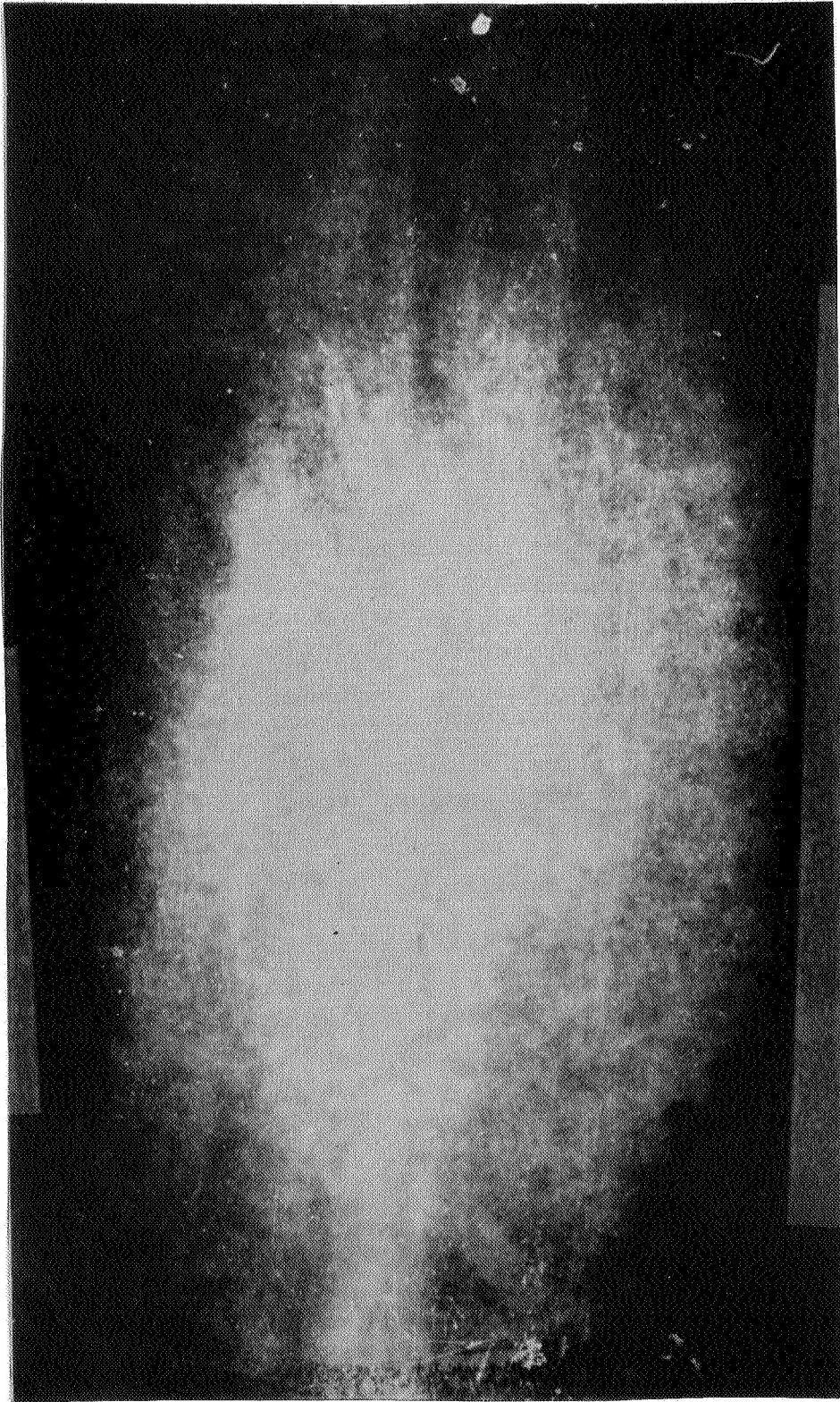


Figure 3. Photograph of Noctilucent Clouds. Crape and Waves.

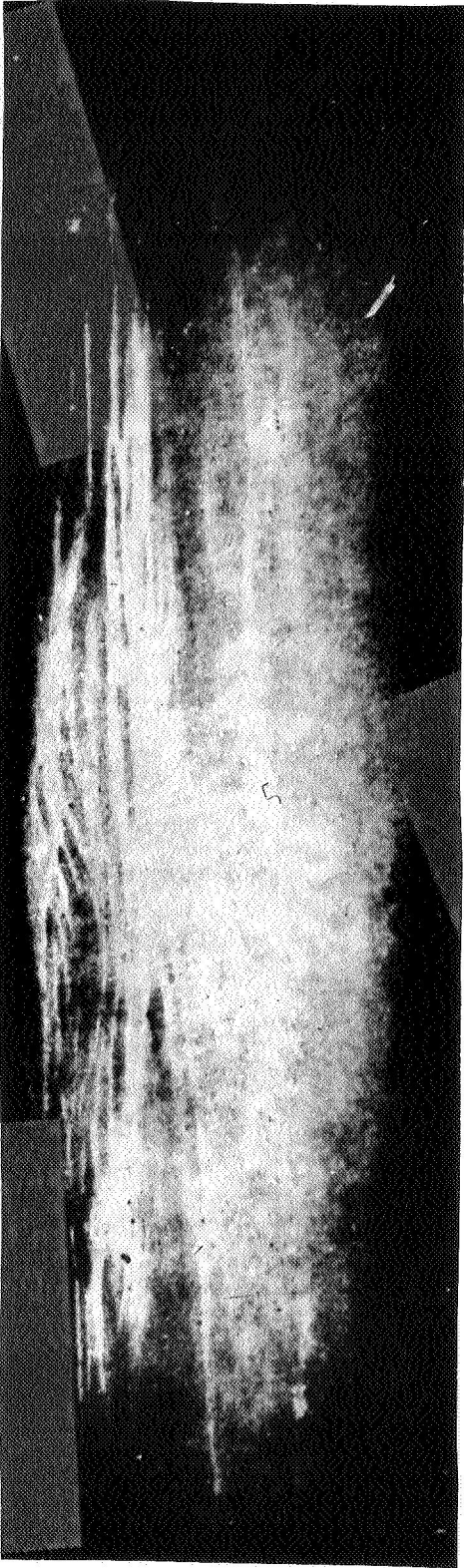


Figure 4. Photograph of the "Stream" of Noctilucent Clouds.

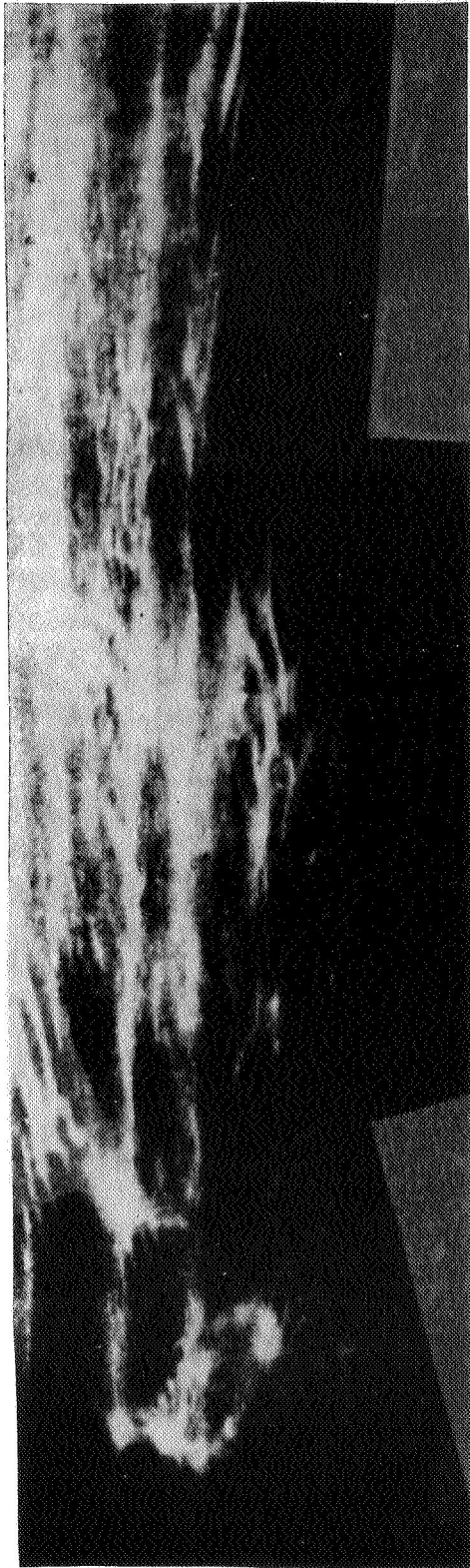


Figure 5. Small Portion of the Wave Field of Noctilucent Clouds. Figure Rotated by 180°.

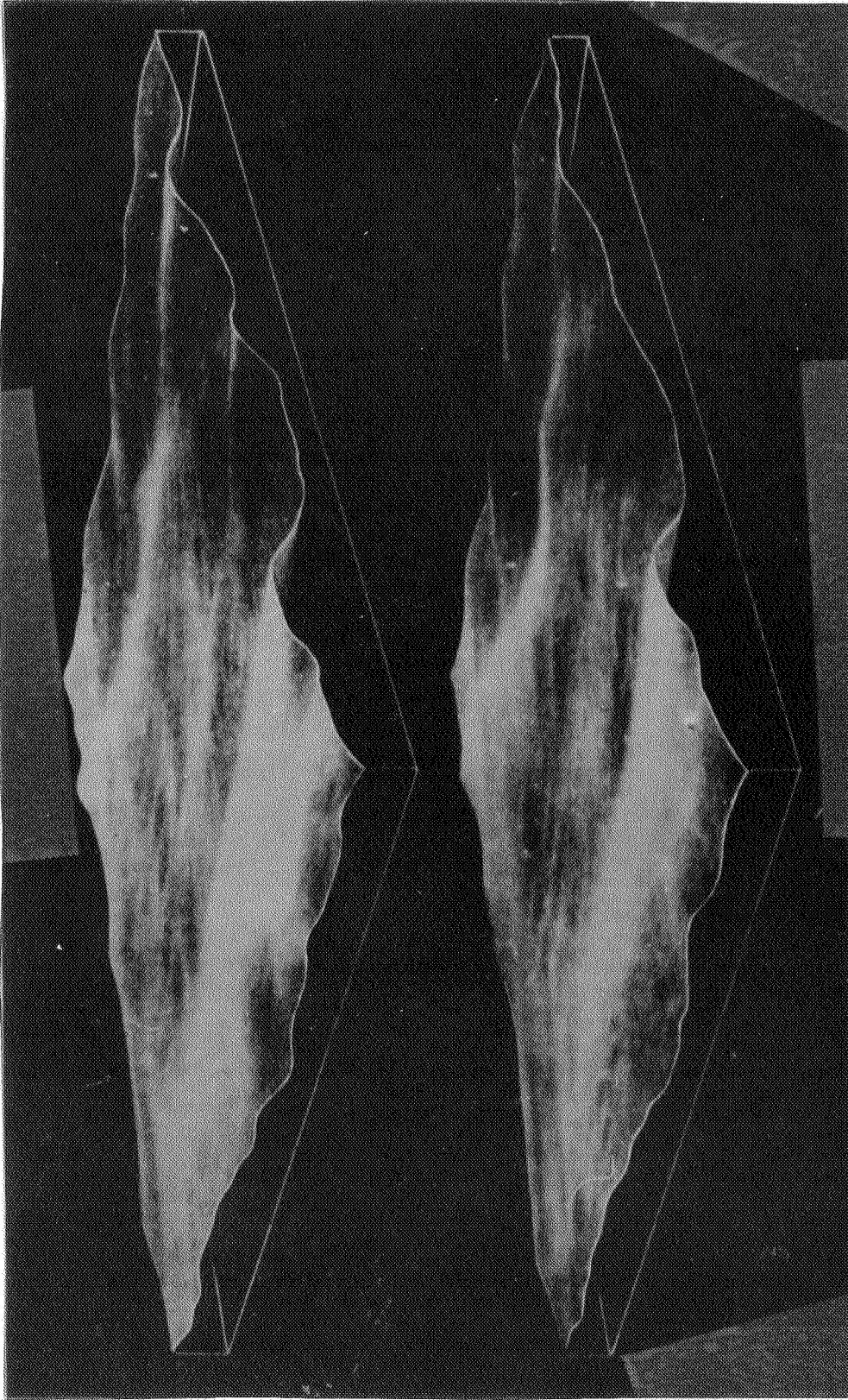


Figure 6. Photographs of Noctilucent Clouds Cut in Vertical Cross Section. The Right Side of Figure (a, b) Shows Invisible Portion of Cloud Surface Which is Only Seen upon Intersection of a High Wave.

The screening effect is observed everytime waves arise whose steepness is greater than the angle formed by the surface of the layer of noctilucent clouds and the angle of sight (alignment) from the observation point.

Figure 7 shows the geometrical conditions for observation of the wave surface of clouds located 10° above the horizon. Taking into account the curvature of the earth's surface, we find the angle of inclination of the cloud layer (taking it parallel to the earth's surface) relative to the observer's horizon plane. This angle is close to 5° . Thus, the layer of noctilucent clouds located at an altitude 10° above the horizon is observed at an angle of 15° . Consequently, the waves of clouds with a steepness greater than 15° will be seen only from one side and will be covered by part of the cloud surface of the neighboring wave. For example, three cloud layers with intervals between them lie on the path of the line of sight AB.

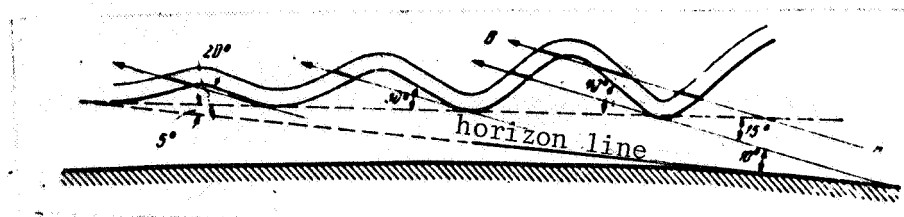


Figure 7. Diagram for Geometrical Conditions for Observing the Wave Surface of Noctilucent Clouds 10° above the Horizon.

As a result, a substantial increase in the visual brightness of the local portion of the noctilucent clouds occurs. The visual brightness increases also because of an increase in the linear stretch of the cloud layer when it is observed obliquely. Vice versa, it is frequently necessary to observe a belt of dark space next to a single steep wave, which corresponds to a large viewing angle on this part of the wavy surface which in turn results in a small linear thickness for the given section of the cloud layer. Similar facts must be taken into consideration in interpreting the results of morphological analysis or photometric measurements. The stated increases in the visual brightness must not be confused with the increase in the optical density of the cloud as a result of strengthening or increasing the number of cloud particles per unit volume. From the morphological viewpoint there is great interest in the study of the conformities in such large-scale evolution of a wavy field as a function of the time of day and the season, thermobaric processes in the lower atmosphere or the latitude and longitude of the location.

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Type IIIc waves belong to the large-scale morphological formations. The length of these waves is over 400 km. Their great dimensions hinder observation. Sometimes, however, we do succeed in identifying these gigantic waves. One such case has already been discussed [1]. On the night of 10/11 July 1959 we photographed two wave crests with a distance of 250 km between them. We used aerial photographic cameras and slow-motion film. On the surface of each crests there were the usual wave fields of noctilucent clouds. In the valley between the crests there were no noctilucent clouds observed. Apparently, the height of these waves was so great that the physical properties of the

mesopause hindered substantial changes which occur during the process of cloud formation. During our data reduction we succeeded in identifying waves 300 to 400 km long. There are obviously longer waves around noctilucent clouds, but they are difficult to identify from the earth's surface. It is feasible that they would be more easily identified if we were to make observations from satellites.

It seems probable that the extra-long waves in the mesosphere play an important role in the process of cloud formation in the mesopause [5]. Further investigations will require large-scale mobile means of taking stereophotogrametric measurements. We will need synoptic maps of the surface relief for the actual appearances of noctilucent clouds as was done in the work of Vitt [7], but only for the more extended surfaces.

Vortex formations are the fourth morphological variety. Their measurements vary within extremely wide limits -- from tens of kilometers to many hundreds of kilometers in diameter. Relatively small vortices are observed visually. The large vortices are revealed during the process of observing material from slow-motion films or as a result of office studies of photographic materials [7]. This structural shape has been less studied than bands or streams. Part of them have a clearly expressed vortex nature. Others are closer to the regions of intense turbulent displacement of air. Figure 5 shows the form of a large turbulent region and the brighter spot within the given field of noctilucent clouds.

The impression arises that some sort of air current concentrated by moisture is invading this section. Several cases have been recorded in which the appearance of noctilucent clouds started with such a local turbulent condensation around which the usual cloud field then took shape. Figure 8 shows such an example in the initial stage of the development of noctilucent clouds from 10/11 July 1951.

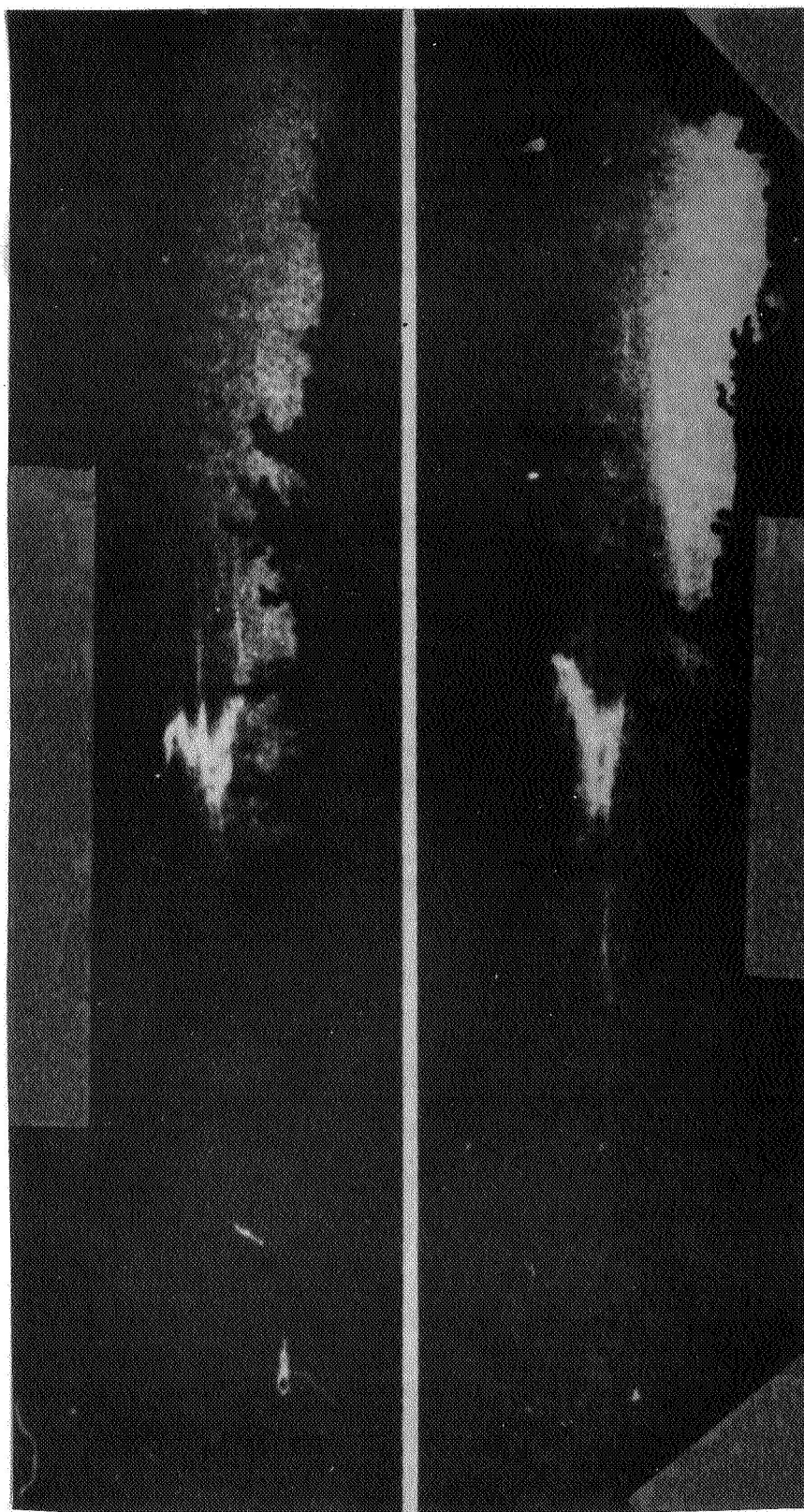


Figure 8. Two Photographs of Noctilucent Clouds. 10/11 July 1951. Sequential.

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